International Journal of Electrical and Electronics Engineering Research (IJEEER)
ISSN(P): 2250-155X; ISSN(E): 2278-943X
Vol. 4, Issue 1, Feb 2014, 161-168

EFFECT OF DC-DC CONVERTERS ON DIRECT METHANOL FUEL CELL OUTPUT

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ABSTRACT

This paper presents an analysis of direct methanol fuel cell (DMFC-mesh and DMFC-foam) systems interfaced to DC-DC converters. The output voltage characteristics of six systems are compared. Experimental results show that DMFC systems present variable, non linear impedance as a function frequency. It is shown, through experimental results, that DMFC systems do not exhibit predictable output as function of duty cycle alone. Consequently, output voltage control through pulse width modulation (PWM) techniques cannot be employed for DMFC systems. The motivation for this analysis is a preliminary investigation into the use of DMFC's as a power source for a prototype Martian Uninhabited Aerial Vehicle (UAV).

KEYWORDS: DC-DC Converter, Direct Methanol Fuel Cell, Duty Cycle, Switching Frequency, UAV

INTRODUCTION

The exploration of the planet Mars will require a diverse collection of exploration vehicles. A concept being studied by the National Aeronautical and space administration (NASA) uses autonomous Uninhabited Ariel vehicles (UAVs) to carry sensors over a wider area than is practical with a Martian surface vehicle. One concept of a Martian autonomous UAV is being developed by a group at the University of Kanas with plans for implementation and test flights in the near future as described in [1].

The atmosphere of the mars near its surface has approximately 1% of the pressure of Earth's near surface atmosphere. Temperature and pressure condition for near surface Martian atmosphere and reasonably approximated by earth's atmosphere at an altitude of about 110,000 feet. Getting an experimental aircraft to this height is to be accomplished by releasing the flyer after a balloon ascent. The flier is then to recover from the release initial drive and perform a set of test maneuvers all in autonomous operation. Completion of the test then calls for unpowered glide and recovery. As current balloon payloads are limited to less than 6 kg, weight is a critical element. Powering the craft and its onboard electronics will initially use batteries as a reliable and predictable power source. This investigation considers an alternate source of power from direct methanol fuel cells [DMFCs]. Beyond possible weight saving there may be thermal effect performance advantage as the plan will experience external temperature from -40 to -50^{0}c. Figure1 illustrate the launch of a mock up vehicle made earlier this year.

Figure 1: Martin UAV Mock up Balloon Launchs

This paper details preliminary studies impacting the selection which DMFC fuel cell type would be most suitable for us in powering high altitude electrical and electronics applications.

Direct methanol fuel cells can be accommodating applications of either high efficiency at lower power transfer, or high power transfer at low efficiency. These features can be implemented for a given fuel cell DC power system by simply adjusting the switching frequency of the DC-DC converter while maintaining the duty cycle constant. One such application is vehicular system, where the amount of power needed varies widely, and of particular interest here, and stationary power systems for remote locations.

In this paper, six types of DMFC-DC converter system are experimentally evaluated over a selected switching frequency range at three predetermined duty cycles of the DC converters. DMFC Nickel-mesh-buck/boost/buck-boost and DMFC Nickel-foam-buck/boost/buck-boost electrode

Experimental result suggest a correlation between the DC converter type, its switching frequency, power source, and the output of the DC system, sequential switching operation i.e, duty cycle and switching frequency, along with the type of DC converter employed are factors determining the maximum power transfer of the system. Normal operation, reliability and life time of DC power sources are negatively affected by the sequential switching within any DC power systems. Direct methanol fuel cells (DMFC) impedances vary nonlinearly; therefore the sequential switching process employed in system voltage regulation can unexpectedly alter the system output voltage.

METHODOLOGY

The DMFC –mesh and DMFC-foam present different impedance characteristics, due to the nickel electrode geometries. Impedance measurements of DMFC-Ni-Mesh, and DMFC-Ni-foam fuel cells were conducted at the centre for Advanced Vehicular System (CAVS) at Mississippi state university.

A signal generator, interfaced to a computer system, was used for data collection. Three type of DC-DC converter were used; buck, boost and buck-boost convertor. Figure 2 Shows the DC-DC buck converter interfaced to a DMFC circuit. The DMFC power source equivalent circuit in figure 2 has its complex impedance approximated with a parallel network of a capacitor, *IM (Z)*, representing the imaginary component, and a resistor, *Re (z)* for the real component.

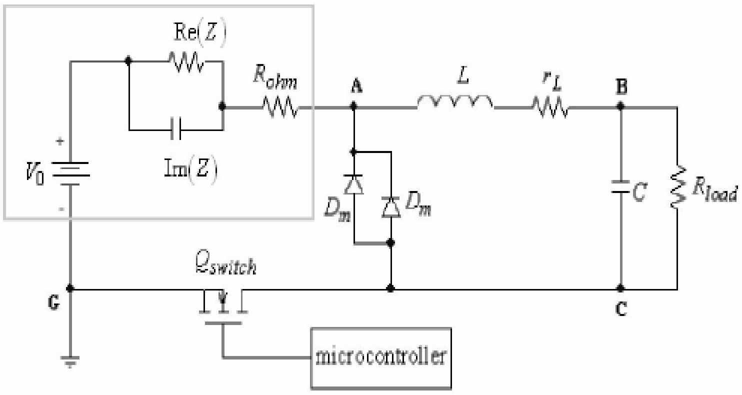

Figure 2: Buck Converter Driven Power System

For each DC power source (DMFC-mesh and DMFC-foam), the switching frequency of MOSFET gate signal was increased from 200Hz to 6 KHz, in increments of 200Hz, at predetermined duty cycles. The pulse width and the switching frequency were generated by the microcontroller. The gate triggering characteristics were implemented through assembly language algorithm and altered manually through interfacing software. Three duty cycle values were selected, as the most practical choice in real application: 50%, 65%, 80% For each duty cycle switching frequency pair, the input voltage value (A-G) and the output voltage values (B-C) were recorded. System input and output voltages were measured with a bench millimeter.

To compensate for the DMFC electrochemical response to change of frequency five to ten minute were allowed between consecutive measurements. In this way the electrochemical reaction reached equilibrium at the time of measurement. Data analysis and graphical representations were performed using MATLAB.

DIRECT METHANOL FUEL CELL

Discovered by William grove in 1842, fuel cell applications expanded from pure novelty to real life applications e.g. NASA's Space Shuttle program. Fuel cell classification is made based on the type of electrolyte or/ and based on the fuel used. In recent years, new fuel were added to the hydrogen only fuel cells, such as ethane, formic acid etc.

Direct methanol fuel cells are less expensive to manufacture and operate, thus reducing the risks associated with the pressurized and /or cryogenic storage of hydrogen fuel. Instead a liquid solution of 10-20% methanol is used to operate the cell. The reduction reaction at the anode is described by

$$CH_3OH + H_2O = CO_2 + 6H + 6e^- \tag{1}$$

At the cathode, the oxidation reaction is described by:

$$3/2O_2 + 6H^+ + 6e^- = 3H_2O \tag{2}$$

In the fuel cell, the temperature T is constant, while the change in molar enthalpy and molar entropy determine the change in molar Gibbs free energy:

$$\Delta\bar{g}_f = \Delta\bar{h}_f - T.\Delta\bar{S} \tag{3}$$

Therefore, the voltage across the fuel cell is the change in the molar Gibbs free energy (negative) for the reaction divided by the electric charge flowing through the external circuit, for the reaction takes place:

$$V=\frac{\Delta g_f}{12.f} \tag{4}$$

Where V is the fuel cell output voltage, $\Delta g_{j,}$ Gibbs free energy of the system, Faraday number. The frequency dependence of fuel cell impedance is a function of the double- layer capacitance [6] and is different for the planar catalyst model and the porous catalyst model [6]. In addition, the redox reduction reaction occurring in the fuel cell involves an adsorption step giving rise to an inductive behavior at low frequencies (~~0.6 Hz) [8]. The impedance response of polymer electrolyte membrane (PEM) fuel cells is a combination of the response of the anode and cathode half cells, with different time constant and frequency dependencies [6].

Due to ease of manufacture, storage, transportation and safe operation, direct methanol fuel cell (DMFC) have been developed and implemented as power sources for light vehicles like Honda scooters.

Expanding the range of applications of DMFCs to medium and heavy vehicles applications requires a detailed and in depth knowledge of DMFC characteristics under various regimes of operation, especially sequential switching mode.

Direct methanol fuel cell (DMFC) are less expensive to manufacture and operate, thus reducing the risk associated with the pressurized and/or cryogenic storage of hydrogen fuel .Instead a liquid solution of 10-20% methanol is used to operate the cell.

Theoretically, the maximum possible voltage that could be obtained from a direct methanol fuel cell is the result of converting all the waste heat into useful work [2]-[5].

$$V_{MAX} = \frac{-\Delta \bar{h}_f}{12.F} = 0.9V \tag{5}$$

Where V_{max} is the fuel cell maximum output voltage, Δh_f, the change in system enthalpy, and F is faraday number. Figure 2 shows the operation of a typical direct methanol fuel cell.

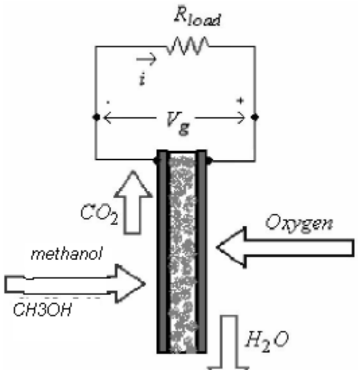

Figure 3: Direct Methanol Fuel Cell Operation

The frequency dependence of fuel cell impedance is a function of the double-layer capacitance [6], and is different for the planar catalyst model and the porous catalyst model [7]. In addition, the redox reaction occurring in the fuel cell involves an adsorption step giving rise to an inductive behavior at low frequencies (~0.6Hz) [8]. The impedance response of polymer electrolyte membrane (PEM) fuel cell is a combination of the responses of the anode and cathode half- cells with different time constants and frequency dependencies [6]

EXPERIMENTAL RESULTS

The impedance of two DMFC, Ni-mesh and Ni-foam electrodes were measured. Over the frequency range considered 0.1 Hz to approximately 10 KHz, the impedance of both DMFC are nonlinear. Impedance plots for both DMFC –mesh and DMFC-foam, presented in figure 4, show a non linearity dependence to signal frequency, and increasing

discrepancy of impedance magnitudes with the increasing of frequency. Consequently, the power transferred from DMFC source will exhibit different values at any particular switching frequency and duty cycle. For the two DMFC systems in boost and /or buck boost interface.

Measurements on DMFC –buck converter power system were performed for Ni- mesh electrode DMFC and for Ni- foam DMFC. Converter switching frequency ranged from 200 Hz to 6 KHz, in increments of 200Hz.

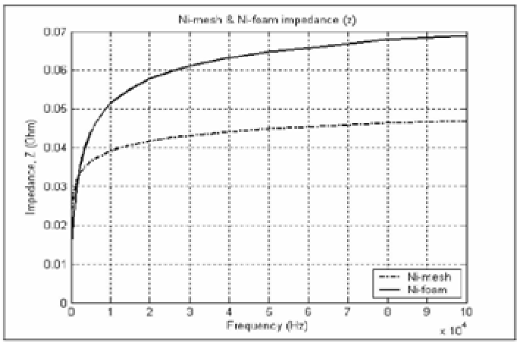

Figure 4: DMFC - Mesh and Foam Impedances as Function of Frequency

Output voltage characteristics for DMFC mesh and DMFC foam- boost converter systems are shown in figure 5 and 6.

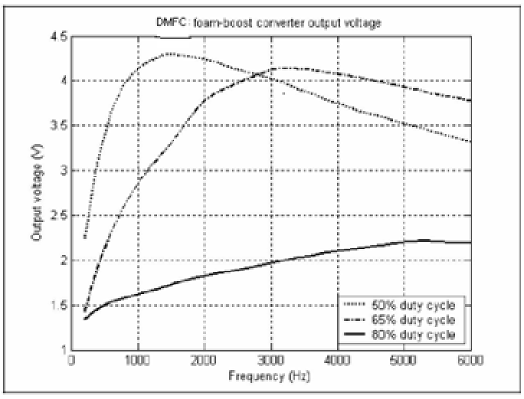

Figure 5: DMFC – Mesh Boost Converter Output Voltage as Function of Frequency

Buck –boost converter systems exhibit an inverted polarity of the output voltage, as compared to the input voltage. This particularly excludes the use of electrolytic capacitors for the output filter. For particularly purposes, a ceramic capacitor of 105.4 Nf was used.

During sequential switching DMFC mesh & foam output voltage are lower than their respective open-circuit voltage. The electrochemistry within each fuel cell is dependent on circuit current during the on cycle.

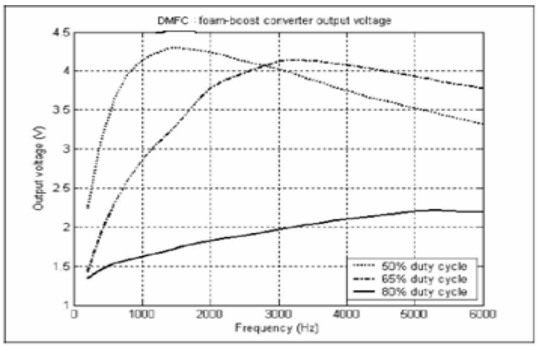

Figure 6: DMFC - Foam Boost Converter Output Voltage as Function of Frequency

System output voltage, measured across load terminals, is dependent on the switching frequency as shown in figure 7 and 8.

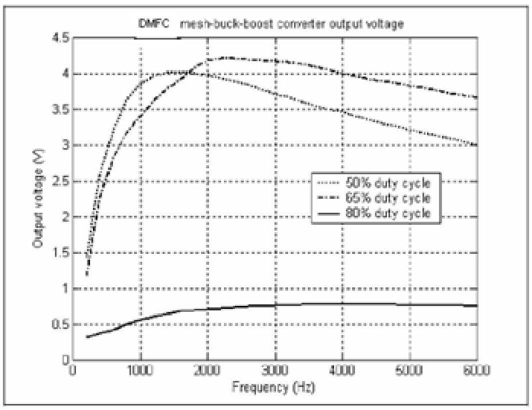

Figure 7: DMFC - Mesh Buck-Boost Converter Output Voltage as Function of Frequency

Thus there is a direct dependence of fuel-cell chemical activity to the switching frequency and duty cycle operation of the converter. The output-input conversion ratio for each DMFC-DC converter system topology does not reflect the duty cycle proportionally at a given switching frequency.

CONCLUSIONS

In the DMFC mesh-boost converter system the maximum output voltage is achieved at 65% duty cycle as the switching transistor operate at a switching frequency of 1400 Hz.

Direct methanol fuel cell nickel-foam electrodes exhibit different performances than the DMFC Nickel- mesh electrodes. For the DMFC foam-boost converter system, operation at 50% duty cycle assures the highest output voltage at switching frequencies below 2800 Hz. Switching frequencies above 2800Hz and duty cycle of 65% operation determine maximum system output voltage. Unlike DMFC mesh-boost converter, the system operation at 80% duty cycle yields lowest output voltage over the entire switching frequency range considered in this research.

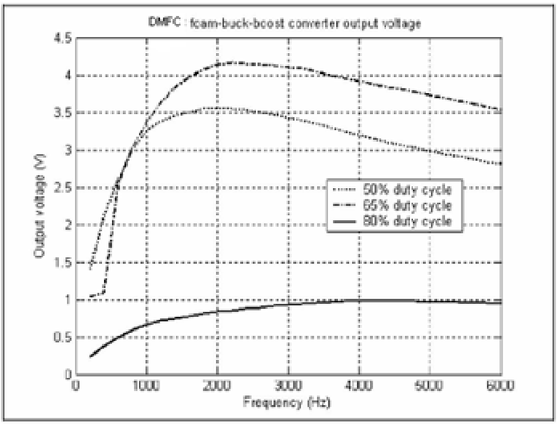

Figure 8: DMFC-Mesh Buck-Boost Converter Output Voltage as Function of Frequency

The DMFC-mesh buck boost system, switching frequencies in the range of 200Hz to 1.8 KHz, and operation at 50%duty cycle, exhibit maximum output voltage. System operation at switching frequencies above 1.8 KHz achieves maximum output voltage when operating at 65%duty cycle. Unexpectedly, system operation at 80% duty cycle is characterized by lowest output voltage as compared to 50% and 65% duty cycle regains. For DMFC mesh-buck-boost converter system, maximum conversion ratio is achieved at 65% duty cycle, over the entire switching frequency range for

the DMFC foam-buck-boost converter system maximum output voltage, and consequently maximum power transfer, is achieved at 65% duty cycle and 2.2 KHz switching frequency. System operation at 80% duty cycle resulted in lowest output voltage, and implicitly lowest power transfer, over the entire switching frequency range. System operation at frequencies lower than 500 Hz has yielded maximum output voltage for 50% duty cycle. Overall operation at 80% duty cycle did not produce a maximum performance for DMFC foam-buck-boost system at any switching frequency.

All of these results are preparatory considerations in the design of a prototype fuel cell. The next phase of testing will incorporate environmental testing with sample loads. While this application is exotic, the authors have expectation of many more potential vehicular applications with a relatively novel power source.

The authors acknowledge the key support of the Kansas NASA EPSCoR program and the Kansas space grant consortium in funding the research efforts detailed in this paper.

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